ECONOMIC FEASIBILITY OF AN OKLAHOMA SWITCHGRASS BIOREFINERY: WHAT ROLE DOES INFRASTRUCTURE PLAY?

By

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ECONOMIC FEASIBILITY OF AN OKLAHOMA SWITCHGRASS

BIOREFINERY: WHAT ROLE DOES INFRASTRUCTURE PLAY?

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Abstract:

This research uses a net present value model developed on Microsoft Excel to determine the feasibility and advisability of a lignocellulosic ethanol supply chain in Calvin, Oklahoma. The research addresses challenges facing Oklahoma with switchgrass production. Dedicated energy crops (DEC) such as switchgrass, can be produced on marginal or Conservation Reserve Program (CRP) land. DECs provide an avenue for biomass to be produced while not hindering or competing with conventional crop production or rangeland uses. Considering the advantages of switchgrass biomass production, it is important to establish a successfully optimized lignocellulosic supply chain. Supply chain for feedstock delivery can be difficult to manage and optimize based on the infrastructure, feedstock availability, farm field locations, and length of haul. These factors play a key role in determining the feasibility and are heavily considered for this research due to the limitations faced by Oklahoma's infrastructure and feedstock availability. Transportation cost implications are of most importance when considering a cellulosic ethanol supply chain. For this research, transportation costs were quantified to reflect issues faced within Oklahoma. In conclusion, for the average yield state of 1.5 tons acre^{-1}, a 69 million gallon capacity (50 million gallons production capacity) biorefinery there will be a required 81,707 truckloads per year. In addition, in the average yield state of nature, under no given price are the projects feasible. Compared to states with a busting corn market with higher yields, multiple inputs, and improved rural infrastructure, Oklahoma has to pay a high premium for the delivery of feedstock. Into the future, Oklahoma will have to improve rural infrastructure and improve yields acre to become profitable.

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INTRODUCTION

The Energy Independence and Security Act of 2007 (EISA) was enacted by the United States congress to move the US in a direction towards energy security and independence, protect consumers, and assist in lowering GHG (green-house gas) emissions (Lim & Ouyang, 2015). After 2007, The U.S Congress passed the Renewable Fuel Standard Act (RFS). This mandate set an annual domestic production target (of renewable fuel) to reach 36 billion gallons by 2022. In 2018, the United States consumed roughly 1.9 billion gallons of biodiesel (EIA, 2019). Current consumption levels are an improvement over the last decade with only 0.30 billion gallons of biodiesel consumed in 2008 (EIA, 2019). It is likely that most consumption came from the production of corn ethanol which is a conventional/ first-generation biofuel (Lim and Ouyang, 2015).

Biofuels made from corn or soybeans, directly compete with food or intermediate products for feed or food manufacturing. Dedicated energy crops, such as switchgrass, are feedstock for second-generation biofuels (Lu et al. 2014). These non-edible crops (switchgrass, miscanthus, corn stover) are produced for the sole purpose of alternative fuel source production. While conventional biofuel production typically competes directly with food manufacturing, second-generation biofuels produced from dedicated energy crops do not. Conventional biofuels act as a segue into a more reliable advanced biofuel supply but are not sustainable in the long run due to competition among sectors of the economy. In the current state of technology, transportation and storage costs associated with advanced biofuels are considerably high (Aden, 2008, Lee, 2018, Marvin et al. 2011, Zhang et al. 2016). So, how can we establish the feasibility of an Oklahoma switchgrass biorefinery considering the challenges faced by the ethanol industry? This research will examine the beginning and end of the supply chain to see how feasible cellulosic biofuel production can be in Oklahoma.

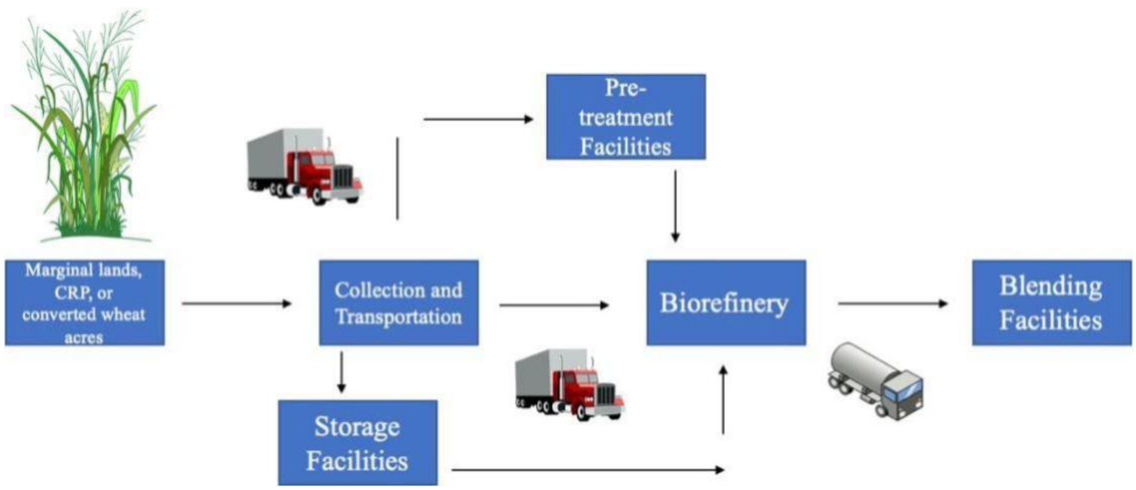

Figure 1. Feedstock to Ethanol Supply Chain

As can be seen in Figure 1, the supply chain for second-generation biofuel production begins by contracting marginal, Conservation Reserve Program (CRP) land, or converted wheat land for switchgrass biomass production. For this research, acres that are currently in wheat production are considered as potential areas for switchgrass production due to the decline in wheat price bushel^{-1} of \$8.50 in 2012 to \$4.80 in 2019 (NASS, 2019). The decline in wheat price gives a wheat producer little incentive to produce. Dedicated energy crops may provide a new revenue stream for wheat producers. The opportunity cost of producing switchgrass must be greater than the opportunity cost of producing wheat in order for a wheat producer to want to convert their land. Once land availability is established, a contract between the farmer and ethanol producer is created. This contract will specify who bears the cost or risk at what point in the production of biomass (seeding, harvest, collection, etc). Biomass is then produced, harvested, and transported to a storage facility, pre-treatment facility, or directly to the biorefinery. Biomass is stored for no more than a year to ensure energy content within harvested biomass is high enough for feasible production. Pre-treatment facilities will process biomass to increase conversion of biomass tons to gallons of ethanol (Agbor et al. 2011). Not all biomass in the supply chain will be pre-treated because of the opportunity cost of doing so at some farm field locations, i.e. if the farm field location is closer to the biorefinery than a pre-treatment facility, then it would not be feasible or advisable to pre-treat initially before converting at biorefinery. Once biomass arrives at the biorefinery, ethanol is produced using a thermochemical conversion process. Ethanol may be refined and then loaded onto tanker-trucks to transport to blending facilities. Blending facilities will purchase ethanol at a wholesale price and mix the product with gasoline to create an ethanol/gasoline blend. The blend of gasoline and ethanol create a fuel alternative for consumers at the gas pump.

Table 1. Biorefinery Capital Costs from Previous Studies

Source	Capital Costs (Million Dollars)	Adjusted for 2019 (Million Dollars)	Capacity (million gallons)	Feedstock Type	Capital Cost per Gallon ($)
Humphreys (2012)	279.5	309.46	75	Switchgrass	4.13
Haque et al. (2014)	379.0	406.97	189	Switchgrass	2.15
Zhang et al. (2016)	333.1	352.80	50	Switchgrass	7.06
Lee (2018)	220.1	222.81	68.9	Switchgrass	3.23
Marvin et al. (2011)	272.5	307.95	56	Barley, Stover, Wheat Straw	5.50
Aden (2008)	231.7	273.57	87	Corn Stover	3.14

2019 dollars calculated with CPI Calulcator (www.in2013dollars.com)

Capital costs from previous research are presented in Table 1. The costs were adjusted to represent construction costs in 2019 dollars. data presented in table 1 provide insight into the extensive capital costs of a biorefinery. While each bioethanol plant in Table 1 are lignocellulosic bioethanol producers, only 4 of which are switchgrass-bioethanol producing plants. The other two cellulosic biofuel plants show the cost of construction for other cellulosic feedstocks that are common inputs in areas where switchgrass is unavailable or not economically viable. Differing input types in this case can be compared since they are all based on a lignocellulosic feedstock conversion.

High capital costs of construction for some biofuel plants presented in Table 1 can be worth the cost if the refinery can produce ethanol at capacity each year. In the case of our case study biorefinery, 69 million gallons is the capacity to produce with an actual production level of roughly 50 million gallons. Furthermore, if a plant can produce at capacity year-round then costs of production can be spread out amongst more gallons of ethanol produced. Dividing capital costs among gallons produced ensures least cost gallon of ethanol-1. In addition, efficiency on conversion of switchgrass (gallons per ton of biomass) has an impact on a producer's ability to create ethanol at a lowered cost.

Initially, it seems that choosing the first optimal transportation route would be correct. However, shortest distance between farm field location and biorefinery might not allow for efficient travelling causing issues within the supply chain. Since trucking is the preferred form of transportation for a lignocellulosic biomass supply chain within Oklahoma, a route with quality or paved roads that are regularly maintained by the city or county will be an ideal choice. The target location in question could be the same considering different routes of transport. However, transportation of biomass costs would not be as efficient since trucks will have to use alternative routes.

An important notion is the infrastructure of Oklahoma as a whole, and more specifically the infrastructure in rural Oklahoma (such as Calvin). This research is most interested in considering the feasibility of a switchgrass ethanol supply chain when accounting for sub-par road conditions. According to a report conducted by the American Society of Civil Engineers (2018), the state of Oklahoma received a C minus on infrastructure as a whole, i.e. bridges, roads, sewage, aviation, etc. Additionally, the state received a D grade for road quality, i.e. pavement smoothness, maintenance, and congestion (ASCE, 2018). The grade of road condition is based on how much money per year Oklahomans pay in taxes, fees and licensing and how much of that money is diverted to taking care of road quality. Currently, 71% of the total 1.2 billion paid in taxes per year does not go towards road maintenance (ASCE, 2017). Furthermore, The Oklahoma Department of Transportation does not perform maintenance or quality checks on countyroads, city streets, or turnpikes. According to Oklahoma.gov (2018), 1.91% of total rural roads in the state are in poor condition and lack the ability to handle large trucking traffic. Considering most of traffic congestion and road damage will take place on rural roads (Lee, 2018), it is important to determine where poor road conditions are located and to determine which area in Oklahoma can be susceptive to a large influx of biomass delivery trucks.

Rural road classes in Oklahoma are directly related to the amount of traffic the road can handle, and most importantly the quality of the road. For this research, the road classes of most concern are Rural Principal Arterial roads, Rural Minor roads, Rural Collector roads, and Rural Local roads (ODOT, 2019). The road classes mentioned here are what a Calvin based cellulosic ethanol producer would be facing when transporting biomass and ethanol to and from the plant. Rural Arterial roads provide the interstate system with high density that serves a rural area with a highway system, Arterial roads are the best condition and largest roads in rural areas. Rural minor arterial roads link cities and larger towns, but do not provide an interstate system. Rural collector roads are assumed to be less quality than arterial, do not provide interstate, and can handle only agricultural traffic with moderate speeds. Last, the rural local road system provides access to farmland and only provides short distances. Road classes and the related quality of each was derived from the Oklahoma Department of Transportation's 2019 report.

It is assumed two roadways most affected by increasing trucking traffic on the roads will be Rural Collector and Rural Local roads (ODOT, 2019). Both of the road classes have very little infrastructure in they are only able to handle exactly the population of the area (ODOT, 2019). Increasing traffic on the roads in question would cause damage that would hinder the local economy and could hurt local farmers. The goal of this research is to assist in considering the advisability in creating a new market and assist rural economies with biomass production. In addition, Long-haul semi-trailer trucks with 3-5 axles are the equivalent of 1,408 normal passengers on a road (Russel et al, 1996). According to The Oklahoma Department of

Transportation trucking regulations maximum weight per axle is 8,000 pounds. Considering that each truck could weigh 20 tons, the destruction to a local road is immense. In addition to road damage, traffic congestion causes issues within smaller communites. Opportunity costs comparison within the state determines which route is ideal for biomass delivery trucks. The map below shows road classification system in Hughes county, Oklahoma where Calvin islocated. The map entails all the rural roads for the county. This is a useful tool to highlight whichareas biomass-hauling trucks will need to avoid when transporting to and from the bioethanolplant.

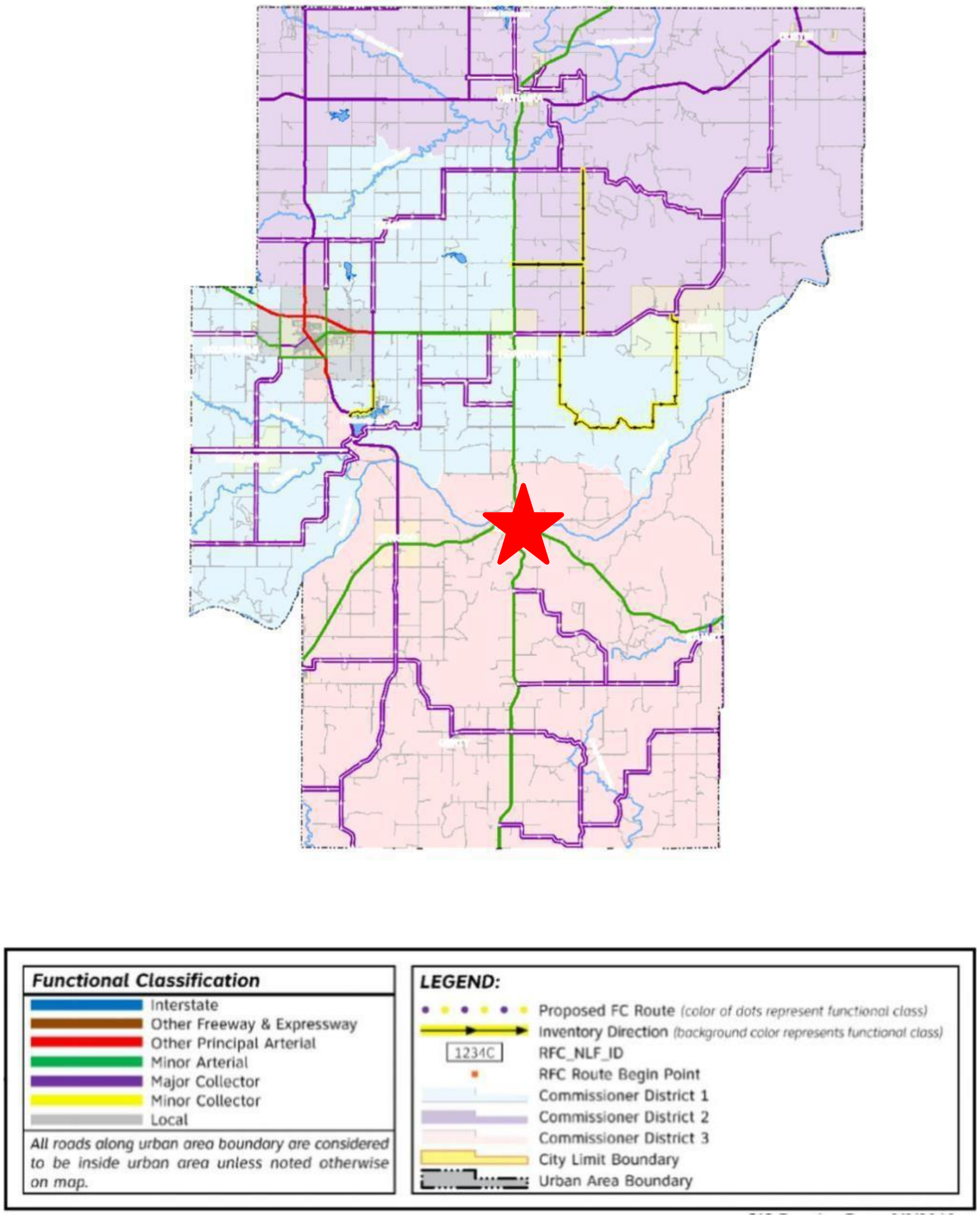

Figure 2. Hughes County Roadmap

In Figure 2, there are four different rural road classes that reside within Hughes County, Oklahoma. The condition of the roads in Hughes County can be differing in terms of quality and size. Initially, it is the best idea to avoid rural local and rural collector roads for as much as trucks are able to do so. The ideal situation for large grain-hauling trucks would be to travel longer distances on both minor and principal arterial roads. Compared to local and collector roads, arterial roads have high density for interstate/intrastate travel (ODOT, 2019). Oklahoma has a total 8,417 miles of principal and minor arterial roads (BTS, 2015). Arterial roads are typically paved to withstand higher traffic and congestion. In addition to the arterial roads, Oklahoma has 25,490 miles of collector and local roadways (BTS, 2015). Collector (major/minor) and local roadways can be paved, but most of the time the roads are either gravel or dirt. Considering the pavement implications, collector and local roads will likely want to be avoided. In total, Oklahoma has 112,940 miles of public road which is a total of every road class both rural and urban (BTS, 2015). Gathering mile numbers in the state allow for managers to get an idea of how many travel miles will be put on trucks each year, how much damage will be caused, and which transportation route would be most cost-effective.

In Figure 2, the red star represents where Calvin, Oklahoma is located. Compared to other Oklahoma cities, Calvin is faced with demographics that are typically faced by a smaller-rural town. Total population in 2019 for Calvin is only 275 people and the poverty rate among the population of the town is 24.7% (Census, 2020). Furthermore, median household income is roughly $31,000 (Census, 2020). Compared to Enid Oklahoma, with a higher population and more infrastructure, of $49,399 (Census, 2020). Demographics of the cities are compared and presented to show how important it is for a biofuel producer to quantify damages to rural infrastructure.

Transportation of biomass to biorefinery can account for up to 12.8% of total supply chain cost (Lee, 2018). Considering the size of Oklahoma, trucking is the cheapest option for transportation when compared to barge or railroad. Multi-modal transportation chains have been discussed in previous studies (Zhang, 2016) but using both train and truck transportation simultaneously is unlikely to be viable given the location of switchgrass within the state. The cost of transportation from field to biorefinery, field to storage facilities, and storage facilities to biorefinery are the main points of interest to a manager. Depending on the location of the fields, and quality of roads costs to a produce could fluctuate greatly.

The aforementioned transportation costs can be better managed with an informed choice for the location of the biorefinery and storage unit(s).Without the assistance of complicated models showing the results, one can assume that closer to the field the refinery as farm field location is, a more cost-savings way of transportation can be adopted. Both in terms of fuel and social costs due to large truck traffic on smaller county roads. Variables including, road condition, population of production area, and best roadway choice are some that need to be included in the decision-making process. Ideally, the chosen location would be one where the positives outweigh the negatives of placement, i.e. the refinery is close enough to the production fields to minimize costs but is not hindering everyday lives of people within the production area. A balancing act of the positives and negatives is important when using a model to pick a location.

Several studies have considered transportation cost of biomass in a multitude of ways (Malmudi and Flynn, 2006; Kumar et al. 2005, Xie et al. 2009, Searcy et al. 2007, Leboreiro and Hilaly, 2010). The breakdown of the previous studies transportation cost is shown in Table 3. Typically, trucking transportation is higher than transportation of biomass through barge or rail (Malmudi and Flynn, 2006, Gonzales et al. 2013). Since trucks can utilize the massive road network throughout the United States, they are able to reach farm fields and the middle of the country more effectively than barge and rail transportation (Gonzales et al. 2013).

Road condition, miles, and pavement quality all are variables for repair and maintenance costs per mile when operating grain-hauling trucks. Repair and maintenance costs are different than damages to pavement from trucks. There is a need to fully estimate the amount of damage that is inflicted upon the trucks themselves from road condition or pavement quality. For this research there will be a base repair and maintenance cost of 10.5 cents per mile (Barnes and Langworthy, 2003). The cost is in terms of 2003 dollars and is inflated to represent 2019 dollars within the model.

A question for this research is what cost items are included in cents ton mile^{-1} for transportation variable costs. For transportation in this case, operator time, and fuel are all variables in determining ton mile^{-1} costs. Harvest, collection, baling loading, and unloading are considered on their own in the form of "harvesting" costs. The issue of adopting a variable ton-mile costs for this research is the daily price change of diesel prices. Since fuel is variable when considering how much variable cost trucks will face ton mile, each day, week, or month could have a very different ton-mile cost (Edwards, 2017). Considering the fluctuation in diesel prices, one must realize the highest bound of ton-mile costs to ensure operations can make a profit in the highest years. It is assumed that if operations can breakeven when diesel price is at the highest, then the biorefinery can make a profit at any price point under the high diesel price.

Weight limits on biomass-hauling trucks are important because it prevents incredible amounts of damage to pavement. Normal wear and tear on a road are expected over years. But, without weight limits, roads are destroyed quicker costing more to the city, state or firm. In Oklahoma, the gross weight limit for a vehicle on interstate highways is 80,000 pounds, and on non-interstate highways 90,000 pounds (ODOT, 2018). Residue haulers are allowed to exceed the weight limit by 5 percent as long as the truck has a special overload permit. But, the truck would not be allowed to travel on interstates if the managers decided to overload the truck not exceeding 5 percent over the original limit (ODOT, 2018). Exceeding weight limit amounts per truck would be useful if transportation of biomass would not take place on interstates. In the case of Calvin, it is a possibility since most are arterial roads used for trucking commodities from farm field locations.

Reasoning for exploring the implications involved with biomass transportation is important because total transportation cost is a function of rural road classes, distance, number of trucks, fuel, and labor cost. Different rural road classes have differing purposes, and as such, each cannot handle the same traffic conditions or types of vehicles. Considering that each rural road class has different purposes, there will be varying amounts of damage to each. For example, rural principal roads will be better suited for more trailer-truck traffic than rural collector roads. There are currently no studies that directly focus on Oklahoma rural roads and the damage that could be caused from increases in grain-hauling traffic. To get an idea on challenges that the Oklahoma rural road system will face, a study from Texas A&M University was adopted to establish estimated per mile cost of trailer-truck traffic. Damage to roads from trucks per mile cost in Table 2 are as follows: principal arterial ($0.259), minor arterial ($0.359), and collector roads ($0.876) (Fraire et al. 2012). The damage cost are as expected since collector roads are inferior quality to principal arterial roads and collector road damage is considerably more per mile.

Table 2. Rural Road Class Attributes

Road Class	Pavement Quality	Road Damage Cost ($ Mile^{-1})	Miles in Oklahoma	Speed
Rural Principal Arterial	Good	0.259	3,093	70 mph
Rural Minor Arterial	Good	0.359	2,749	70 mph
Rural Collector System	Average	0.876	3,038	55 mph
Rural Local Roads	Poor	N/A	69,038	55 mph

Source: (Fraire et al. 2012, USDOT, 2017)

Evaluating and determining an economically advisable supply chain design for Oklahoma is important for proving its feasibility and establishing a successful cellulosic-ethanolmarket. Numerous studies of cellulosic biomass supply chain design before this research have focus on important parts such as capital costs, availability, uncertainty, storage, and an increase in trucking miles. But, none have considered all previously mention factors for a switchgrass-only supply chain in Oklahoma. Furthermore, no previous studies have covered infrastructure concerns within Oklahoma from increased traffic from transportation of biomass. This study adopted similar models on net present value of a biorefinery to construct a supply chain for Oklahoma and included a consideration for infrastructure damage concerns.

Consideration for infrastructure damage is important to investors and producers alike due to the state of Oklahoma containing low infrastructure compared to most case-study, corn-belt states such as Indiana or Nebraska (Tyner, 2012). In more rural areas of Oklahoma, infrastructure is more susceptive to damage from increased road traffic from construction of the biorefinery and transportation of biomass. Compared to corn-belt states, Oklahoma does not produce enough corn to justify improving rural road conditions. In addition to uncertainty and availability of biomass, roadway condition can cause numerous logistical problems and will force the biorefinery to spend money to fix roads or lose out on opportunity costs from increased traffic. Building upon previous studies, this research focused heavily on determining the feasibility of transportation to deliver biomass and ethanol and to test whether or not switchgrass could be the sole biomass input for a supply chain

For a comparative look, Corn Belt states have a bustling corn market and in many cases the road condition of these states, specifically rural roads, are in better condition than Oklahoma roads (Tyner, 2011). Considering the level of corn production, the states are already susceptible to increases in road traffic per year. In addition to road condition, Corn Belt states have a high amount of corn Stover left over after corn harvest. Corn grain is an input for first-generation biofuels and this biofuel market has been profitable because of availability (Taheripur et al. 2013). In contrast, Oklahoma does not have the same level of corn production, nor does it have the same roadway availability to fields (NASS, 2019). Due to less production on rural roads, Oklahoma will face considerably worse infrastructure implications compared to Corn Belt or other case-study states that have a successful rural economy.

Oklahoma was ranked number 31 out of all the states on infrastructure in 2017 (US News, 2017). Better infrastructure implies the state's ability to handle a biofuel market. This research aims to consider how Oklahoma's road condition can accommodate a biofuel market considering the road conditions compared to states where a biofuel market is prevalent. An important notion, Oklahoma has an opportunity for commercial scale production of switchgrass. Switchgrass is allowed to be established and harvested on Conservation Reserve Program or CRP land (LeDuc et al. 2016). CRP land is conservation land that does not permit the production of row-crops on it during a period of time (FSA, 2020). Since switchgrass is a native prairie grass, it is allowed to be grown and harvest on CRP without repercussion (FSA, 2020). CRP land represents a competitive advantage for Oklahoma because of the amount of reserved land available in the state. As of January 2020, Oklahoma currently has about 10,000 acres enrolled in the program (FSA, 2020). However, if there is little or no access to the reserved land, then CRP land will represent more costs than the biomass is worth to collect.

Proper storage schemes have been a question for hopeful – and current ethanol producing refineries. Storage schemes are the umbrella term that represent how to properly harvest, collect, bale, and lastly store the biomass (Mooney et al. 2012). Multiple storage scheme options are investigated to determine which is best for switchgrass bioethanol production within Oklahoma. Storage schemes may seem arbitrary and not as important as transportation or conversion costs. But, due to dry matter loss of the biomass after harvest, a biorefinery can stand to lose a lot of money from not properly baling or storing biomass (Lee, 2018).

The definition of dry matter loss is when the cellulose within cellulosic biomass starts to degrade (Ashton, 2010). Dry matter loss occurs when biomass is not used or converted immediately after harvest and is dependent on the moisture content of the biomass, in this case switchgrass. For round and rectangular balers, switchgrass is expected to have a moisture content between 16% and 18% when it is being harvested (Mitchell and Schumer, 2012). The expected moisture content is to mitigate storage losses from baling switchgrass.

Proper storage scheme will alleviate some issues that arise when considering dry matter loss (DML). For example, switchgrass round bales stored inside had 0-2% DML while bales that were stored outside had 5 – 13% of the bale weight lost (Mitchell and Schumer, 2012). Temperature and water are the determining factors when it comes to DML, with a high temperature comes more moisture loss and with an overabundance of water or moisture, the stored biomass can be susceptible to fungi (Mitchell and Schumer, 2012). Finding a balance of water and temperature is what previous studies have considered and tested. Considering outside or inside storage method can change input availability levels to be detrimental to operations.

For this research, storage of switchgrass biomass will be ideally 6 months, but no longer than a year at a time. The storage horizon is determined in part from dry matter loss concerns within switchgrass biomass. The longer the biomass is stored, the more moisture weight it will lose (Kumar and Sokhansanji, 2007). Since storage will ideally be 6 months to a year, dry matter loss from storage will not be as grave of a concern as will the loss from collection and transportation of the switchgrass. Transportation of switchgrass can account for 2% – 3% of dry matter loss to a round bale of switchgrass (Kumar and Sokhansanii, 2007). Required biomass converted at the biorefinery will need to be at least 20% over the required biomass to produce at capacity to account for possible matter losses from collection, transportation, and storage.

As can be seen in Table 3, truck transportation cost will be determined from distance variable costs and distance fixed. Table 3 shows previous literatures treatment of distance variable costs Loading and unloading of biomass in this research will be considered as a part of the operational costs of the biorefinery since it is independent of distance travelled. Variable costs of transportation are a function of distance (in miles for this research). But there existsconflicting opinions on what costs should be included in the variable costs per ton mile (Marrison and Larson, 1996). Variable cost per mile is only one part of total transportation costs considered. Distance fixed cost to deliver switchgrass is based upon previous research on hauling distances between 26 and 100 miles per trip. \$2.60 loaded mile^{-1} is fixed cost mile^{-1} based upon 13 tons per trip (Brechbill and Tyner, 2008). Distance fixed value is later adjusted for 2020 dollar value.

Table 3. Variable Distance Cost Sources

Source	Units	Distance Variable Cost	Cost Breakdown
Leboreiro and Hilaly (2010)	ton^{-1} mile^{-1}	0.204	***
Mahmudi and Flynn (2006)	ton^{-1} mile^{-1}	0.224	Wages, fuel, and capital recovery
Xie and Zhao (2009)	ton^{-1} mile^{-1}	0.111	***
A. Kumar et al. (2005)	ton^{-1} mile^{-1}	0.217	Depreciation and return on investments
Searcy (2007)	ton^{-1} mile^{-1}	0.193	***
Marrison and Larson (1995)	ton^{-1} mile^{-1}	0.241	***
Lee (2018)	ton^{-1} mile^{-1}	0.215	***

For this research, Calvin, Oklahoma is the candidate location for a biorefinery. Calvin is located in Hughes County. According to a 2017 estimate from the US Census, Calvin isestimated to have 285 people that reside within the city limits. In addition to that, Calvin has a 29.3% poverty rate. These demographics are brought up to show that the introduction of 18-wheeler traffic within the city can go different ways. 1) If trucking damage is minimized and correct routes are chosen, everyday life within Calvin should not be hindered. 2) If trucking damage is not dealt with, then considering the low population and high poverty rate, it would be difficult for the city to be able to maintain the upkeep on the road.

Overall this study aims to develop a framework for estimating transportation cost for an optimal location and design for a switchgrass biorefinery. Specifically, this research focuses on the feasibility for a switchgrass biorefinery in Calvin, Oklahoma. Determining feasibility began by studying previous literature on single feedstock inputs for a bioethanol supply chain. Where some previous estimates were adopted for Oklahoma. Single feedstock supply is the basis of this research but draws on other supply chain management schemes to adopt a model of transportation costs that will work for Oklahoma and the unique problems that it faces. The capital costs and other costs associated with a bioethanol production supply chain were derived from previous literature. In the end, a net present value of operations for 20 years under different states of nature of yields were calculated to determine if returns above costs are positive and advisable under different scenarios of ton-mile cost to deliver switchgrass and wholesale ethanol prices.

CHAPTER II

OBJECTIVES

The focal point of this research is to determine the advisability or feasibility of a lignocellulosic biomass supply chain for bioethanol production within Oklahoma. To do this, multiple goals will be met:

- Analyze the role of transportation cost faced by Oklahoma ethanol producer in context with other states.
- Implement an NPV model to determine economic feasibility of a biorefinery over a 20-year project life.
- Least-cost estimate for delivered switchgrass from farm-field location to biorefinery.

The objectives above are the issues faced by hopeful and currently operating bio refineries in other states. Currently, Oklahoma is without a commercial scale biorefinery due to the logistical issues involved (Haque et al. 2014, ODOT, 2019). This project aims to answer and solve many questions hindering hopeful managers or investors of a biofuel conversion plant.

Trying to evaluate all the moving parts of a supply chain is difficult. These parts include storage, transportation, harvesting, biomass availability, and conversion rate. These differing variables are hard to combine and compare in the big picture since there is different dollar values placed on each in counties and cities across Oklahoma.

CHAPTER III

REVIEW OF LITERATURE

Since the implementation of the Energy Independence and Security Act of 2007, and subsequently enactment of the RFS, federal agencies have been attempting to implement and establish a new biofuel industry to reduce dependence on fossil fuels (Lee, 2018, Marvin et al. 2011, Tembo et al. 2003, Lim and Ouyang, 2015). Producers have begun using lignocellulosic biomass as an input for producing second-generation biofuels. Examples of operations that use cellulosic biomass for ethanol are Logen, POET, and DuPont. Each year the EPA publishes required blending percentages of cellulosic ethanol with gasoline (Valdivia, 2016). The required blending percentage is assumed to increase each year, causing demand to increase over the years. Producers and blenders of ethanol are switching to more abundant cellulosic ethanol inputs such as switchgrass to keep up with the increasing demand (Lee, 2018, Jin et al. 2019).

Using lignocellulosic biomass such as switchgrass is expected to mitigate competition between the food industry and land used in the production of bioenergy feedstock (Zhang et al, 2016). Switchgrass has potential to become an important feedstock for the biofuel industry (Lee, 2018, Marvin et al. 2011, Lim and Ouyang, 2015). However, high transportation costs, infrastructure concerns such as road quality, congestion, and access to production fields play a large part in feasibility. In addition, cost of corn- based ethanol, cost of gasoline, and the price of crude-oil all factor into the feasibility of cellulosic ethanol production (Lee, 2018, Tyner, 2011, Zhang et al. 2016, Irwin, 2019).

Biofuel plants sell or trade credits, known as Renewable Identification Numbers or RINS, to each other. RINS are a government program that track production levels, where production is taking place, and what percentage of gasoline consumption is ethanol (Irwin, 2019). According to the EPA, RIN credits are production incentives to ethanol-producing biorefineries. When a RIN is retired at a blending facility, the biorefinery that produced the ethanol will receive a payment. RINS are designed to ensure compliance on the part of the biorefineries and to provide an incentive to produce. The change in RIN prices should have little impact on the minimum ethanol selling price, but RINs do impact the spread between gasoline and ethanol prices (Irwin, 2019). When RIN prices decline, ethanol prices fall accordingly (Irwin, 2019). RIN and gasoline price play a large part in amount of ethanol produced, but how many gallons the market demands each year plays a larger role in prices received by the biorefinery. In the current climate, ethanol supply in the market exceeds the demand for ethanol (Irwin, 2019). The oversaturation of the bio-ethanol market is driving ethanol prices lower. This thesis analyzes what the impact oversaturation and low price will have on feasibility of a cellulosic ethanol market within Oklahoma.

It is assumed that with other markets, if there is an over-abundance of supply within the market then there will be little to no incentive for production, i.e. if there is a high supply of ethanol then it will lead to low ethanol prices. However, typical supply and demand assumptions are not the case for cellulosic ethanol. Cellulosic ethanol has a mandate from the US government to produce a minimum number of gallons each year (EPA, 2018). The US government established the required gallons per year mandate to reduce carbon dioxide emissions by the United States (EPA, 2018). Considering the government requirements, cellulosic ethanol will still need to be produced to meet the mandate blending rate of ethanol into gasoline. The relationship between gasoline and ethanol shows that ethanol will be needed, even if there is a low or little incentive to produce ethanol based on price available in the market.

A number of studies have considered multiple feedstock options (Lee, 2018, Lim and Ouyang 2015, Atashbar et al. 2017, Zhang et al. 2016). Multiple feedstocks are considered to assist the biorefinery in producing the required number of breakeven gallons per year. A biorefinery converting at least 2000/Mg or 2,200 tons a day of biomass is expected to meet an internal rate of return (IRR) of 10% (Aden, 2009). Multiple feedstocks such as corn stover, hay, and switchgrass have been considered the most reliable feedstocks to ensure having a constant biomass input supply (Lee, 2018). Multiple feedstock options have been investigated to account for variability in yields of a single feedstock (Lee, 2018, Atashbar et al. 2017, Hess et al 2007, Tembo et al. 2003).With multiple inputs, there will be a minimal concern for yield variability due to diversification of input suppliers (Lee, 2018, Tembo et al. 2003). This study's focus will be on having a single feedstock input, switchgrass.

In addition to land availability, Oklahoma is faced with inferior rural road quality compared to other Corn Belt states (Tembo et al. 2003). In Corn Belt states, such as Western Indiana, the rural infrastructure is more open to an increase in truck traffic due to the production of corn that occurs in these areas (Tyner, 2011). According to the American Civil Engineer Society, Oklahoma ranked 33rd for road quality and top ten in worst bridge quality in 2017 (ASES, 2017). Indiana, the case study state for Tyner (2011), is more inviting to truck traffic than Oklahoma. Tyner (2011) uses a roadway network to estimate the number of trucks on the road each year if a biorefinery was established. Having an improved road system will mitigate some social costs that comes from trucks in rural areas. Oklahoma is not a major corn producing state and rural areas are less established leading to more social costs when trying to determine feasibility for bio-ethanol operations (Tembo et al. 2003). The impending social costs involved in collection of feedstocks and delivery of bioethanol will affect the rate of return for a biorefinery.

This thesis aims to adopt assumptions and methodology used by previous literature (ASES, 2017, Tembo et al. 2003, Tyner, 2011) to quantify transportation costs within Oklahoma.

Some research prefers to charge a transportation cost on a per truck load basis (Gonzales et al. 2013), where the tons per truck is assumed to be uniform and there is no distinction from variable cost from fixed costs. Other research such as, Malmudi and Flynn (2006), Searcy et al. (2007), Kumar et al. (2005), consider truck transportation cost as a function of both distance variable and distance fixed costs. Here, distance variable costs are costs incurred from increasing distances travelled, while distance fixed costs are the same regardless of length of haul (Mahmudi and Flynn, 2006). Lastly, Marrison and Larson (1995) considers transportation cost as a function of loading/unloading cost and variable ton-mile cost. For this research, distance variable cost calculations in addition to repair/maintenance of trucks per mile derived from previous research is the basis of transportation cost of delivered switchgrass.

The existing body of knowledge contains a number of studies considering the feasibility of a lignocellulosic supply chain design and the effect of related gasoline and corn-based ethanol price (Lee, 2018, Atashar et al. 2017, Zhang et al. 2016, Lim and Ouyang, 2015, Marvin et al. 2011). But, none have focused on Oklahoma and the infrastructure quality implications of increased road traffic from production of switchgrass. One study (Tembo et al. 2003) discussed the process of implementing a multiple feedstock input industry within Oklahoma. This study is helpful from a modelling perspective but, the article is outdated in terms technology. The study has a shortfall in it does not quantify infrastructure damage to the state with increase amount of traffic on the roads each year. Previous studies such as, Tyner (2011), have discussed traffic and infrastructure concerns, but did not incorporate every variable that Oklahoma needs compared to Indiana. What this study aims to do to build upon existing literature (ASES, 2017, Atashbar et al. 2017, Aden, 2009, Lee, 2018, Zhang et al. 2016, Lim and Ouyang, 2015, Tyner, 2011,Tembo et al. 2003, Irwin, 2019, Jin et al. 2019, EPA, 2018, Hess et al 2007, Kumar et al. 2005, Malmudi and Flynn, 2006, Marvin et al. 2011, Marrison and Larson, 1995) to determine the advisability of a switchgrass based ethanol supply chain within Oklahoma. The results of this research will be of interest to ethanol producers, rural citizens of Oklahoma, and policymakers.

CHAPTER IV

METHODOLOGY

Determining whether a lignocellulosic biorefinery is profitable for Calvin, Oklahoma is heavily dependent upon the wholesale price of ethanol and per-ton mile cost to deliver switchgrass to a biorefinery. The goal of this research is to determine the advisability of a lignocellulosic biofuel plant in Oklahoma. For example, if the net present value (NPV) model has a positive net present value, the project is advisable under the given circumstances. The NPV model assumes a 20-year time horizon with varying per-ton mile transportation rates. The plant was assumed to be located in Hughes County near Calvin, Oklahoma.

To conduct the sensitivity analysis for a biofuel plant, numerous costs must be known or accurately estimated. Furthermore, costs of procurement and delivery of biomass are the main drivers in determining feasibility. To start, a user of the feasibility tool can input data on their project and determine if the plant can turn a profit over a range of ton-mile costs and wholesale ethanol prices. To implement calculations, a biorefinery manager can input biorefinery capacity (gallons of ethanol produced), financing rate, discount rate, project life, capital investment ($), ton-mile cost ($), wholesale ethanol prices ($/gal), switchgrass (biomass) yield per acre, miles per trip, conversion rate (gallon per ton) and backlogging (typically 2/3 of total delivered miles).

Revenue of the plant is based upon a biorefinery's capacity in gallons of ethanol produced (each refinery is assumed to always produce at capacity). Capacity in gallons is multiplied by wholesale ethanol price in dollars per gallon. The following will result in a rough estimate of the returns before cost for a biorefinery producing at capacity each year. To ensure that a given biorefinery is producing at capacity, it must procure, in addition to tonnage required to operate, at least 10% of the total biomass required to produce at capacity. Our sensitivity analysis tool assumes a 10% moisture or dry-matter loss in transportation. In order to counteract dry-matter loss in transportation, the system takes 10% of required harvested tons and adds the amount to biomass needed to produce at capacity. In the end, required harvested tons of biomass will be 110% of what is actually required in terms of dry tons of biomass. Revenues are established and set as an equal value for the life of a project. In the case of this research, the project life is 20 years.

Costs for the procurement and delivery of switchgrass are considered simultaneously as the user inputs the unique data relating to a biorefinery project into the tool. The goal is to consider every initial and procurement cost for the delivery of lignocellulosic biomass. Many of the costs considered are based on required acreage at a given level of yield per acre of biomass. For example, establishment costs for switchgrass are based on per acre estimates for initiating seeding, watering, and fertilizing. Establishment cost per acre is multiplied by the required number of acres a biorefinery needs to produce at capacity. In addition, harvesting costs and production costs such as baling, and tractor operating are as well multiplied by the required amount of acreage for the biomass supply chain.

Other costs such as, the per year payment for biorefinery capital costs are a function of the initial capital cost, project life, and financing rate. Per year payment on capital costs is not a per acre expense but rather a per year expense. Assumption of the analysis is that the bioethanol producers don't own their own land. Because of the assumption, there requires a payment to a farmer for land rent charges. The total value year$_{-1}$ of a farmer payment is based upon required acreage multiplied by rent charge per acre.

Transportation of switchgrass is based upon a calculation of variable ton-mile^{-1} costs, distance fixed costs, repair/maintenance to truck mile^{-1}, and damages to roads mile^{-1}. Ton-mile^{-1} value is multiplied by the number of tons to be transported and then further multiplied by the average distance travelled in miles for biomass delivery. Distance fixed cost, repair/maintenance and damage to roads (social cost) are multiplied average distance travelled and then further multiplied by the required number of trucks each year. Number of trucks each year is calculated from 863 pound limit in each truck, each carrying 26 bales. These values are multiplied to calculated total pounds truck^{-1}. From there, the total pounds truck^{-1} is divided by 2,000 pounds to establish tons truck^{-1}. Finally, required biomass tonnage year^{-1} is divided by tons truck^{-1} to determine truckloads required each year.

The values here are multiplied by number of trucks required because each cost is in terms of one truck. Each value is added together for total transportation costs per year. Average distance travelled in miles for a biomass truck is considered to be total distance to a biorefinery plus 2/3 of the distance travelled in miles to the biorefinery. 2/3 of total distance is considered to be backlogging and takes into account cost of trucking after delivery of biomass to a biorefinery. In addition to cost of transportation for delivered biomass, end product or bioethanol transportation to commercial wholesalers or directly to consumers is included as a cost incurred by a bioethanol producer. The cost is calculated as the per ton mile cost multiplied by biorefinery capacity, in our case capacity production is assumed to be 50 million gallons (69 million gallon annual capacity) of ethanol produced in a year. Each year a biorefinery is assumed to produce exactly at capacity. Considering the assumption, calculations for bioethanol transportation are the capacity of a biorefinery multiplied by the original distance sensitivity (ton-mile) cost of .20 ton mile^{-1}. Calculation of total transportation cost is given in the equations below. The summation of distance fixed, distance sensitivity, road damage, and repair/maintenance represents total transportation cost.

*Distance Fixed: $3.10 mile^{-1} * average distance travelled (miles) * truckloads required year^{-1}*

*Distanced Fixed Sensitivity Range: $.20 - $.40 tonmile^{-1} * tonsyear^{-1} * averagedistance travelled (miles) * truckloads requiredyear^{-1}.*

*Repair/Maintenance: $.14 mile^{-1} * average distance travelled (miles) * truckloads required year^{-1}.*

*RoadDamage(Social Costs):$.56mile^{-1} *averagedistancetravelled(miles)* truckloads required year^{-1}.*

Operating costs for production of ethanol are calculated on a per gallon basis. Per gallon cost to the biorefinery producer is based on previous literature (Lee, 2018) assumptions where operating costs are a summation of utilities, labor, and conversion costs. The cost incurred are then established on a per gallon produced basis. Since a biorefinery is assumed to produce at capacity each year, the cost per gallon to produce bioethanol is multiplied by the total capacity of the biorefinery in gallons of ethanol produced. The total value is considered to be the operating costs to the biorefinery on a per gallon basis. Considering costs in this matter allows for a bioethanol producer to determine how many gallons are cost effective for the size and efficiency of bioethanol production.

Finally, total cost incurred to a bioethanol producer are per year payment of the capital costs to establish a biorefinery, establishing costs such as fertilizer and seed, land rent payment to a farmer, harvesting costs such as mowing switchgrass, production costs such as baling and loading tonnage of biomass onto delivery trucks, transportation costs for delivered biomass and bioethanol (end-product), and operating cost to produce ethanol per gallon. The summation of the listed costs is considered as the per year minimum cost to produce gallons of ethanol at capacity each year. Costs here are subtracted from per year revenue to establish profit in dollars in a given year.

For the consideration of feasibility, each year of profits is calculated into present value dollars using a discount rate. Upon the calculation of each year's profits, a net present value analysis is completed and the summed over the life of the project. Summation over the net present values of profits are considered to be the total net present value of the project if it were to begin operations today. Overarching goal to a bioethanol producer is to produce at high enough capacity at a low enough cost to have a positive net present value of the life of the project.

Several variables such as efficiency, road quality, farmer participation, fuel cost, etc affect the profitability-breakeven (where profit = zero) of ethanol. However, a change in crude oil prices or wholesale gasoline prices causes the most fluctuation with cellulosic ethanol prices (Tyner, 2015). If crude oil prices are lower than usual, the demand for cellulosic biofuels will decrease. The decrease in demand will force the price of biofuels to decrease. It is exactly the opposite when crude oil prices are high. The managers of the biorefinery want the crude oil price to stay high. This will increase demand and managers can charge more for their product. Charging more will decrease the number of required gallons to breakeven. We will want to look at different scenarios to ensure breakeven production is possible in times when there is a low market price for ethanol.

In addition to an economic feasibility tool, this research provides economic advisability of a biofuel project. For this research, a project is considered to be economically advisable if the net present value (NPV) of the project over the life is a positive value. In contrast, a lignocellulosic biofuel project with a net present value is less than zero, does not breakeven and is not advisable. Furthermore, results of this research are compared against case-study areas with an improved rural infrastructure.

CHAPTER V

DATA

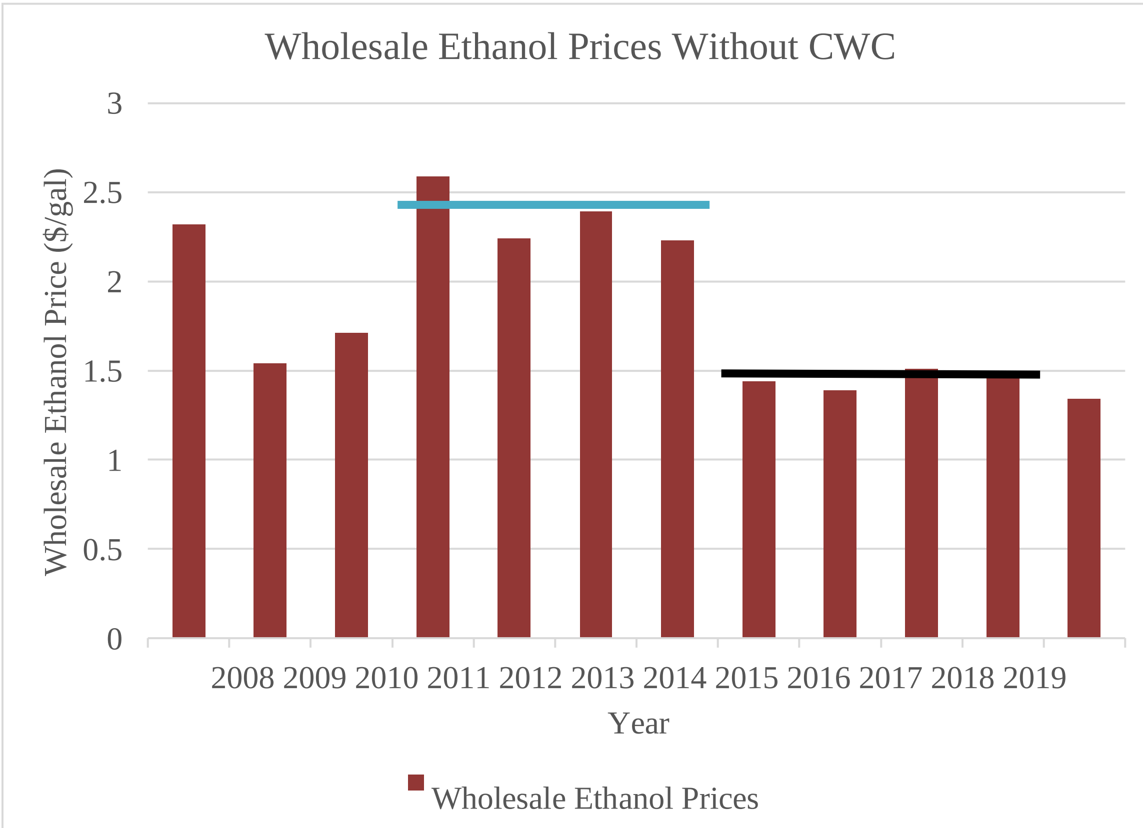

Figure 3. Wholesale Ethanol Prices and CWC (2008-2019)

Wholesale Ethanol Prices and CWC

Historical wholesale ethanol prices without a cellulosic waiver credit can provide some insight as to what actual wholesale ethanol prices may be realized in the future. In Figure 3, the prices are shown without the Cellulosic Waiver Credit added (marketinsider.com, 2019). The prices are reported as the average of the reporting year (marketsinsider.com, 2019). Over the past decade there has been an obvious “high-period” and “low-period” of wholesale ethanol prices. Wholesale ethanol prices are presented to provide a base to begin an analysis. However, the average price will not be considered in calculations

A portion of this research is understanding how the Cellulosic Waiver Credit (CWC) is calculated and what is the determining factor for ending wholesale ethanol selling price. Cellulosic waiver credit is determined based off the spread between wholesale gasoline prices and wholesale ethanol prices. For 2020, the CWC is set at \$1.80 gallon^{-1} (Voegele, 2020). That is, an ethanol blender is willing to pay \$1.80 more gallon^{-1} of ethanol. If the wholesale gasoline price is \$1.67 gallon^{-1} then a blender is willing to pay \$3.47 gallon of ethanol^{-1}. Considering the subsidy will benefit an ethanol blender, the wholesale ethanol price will reflect wholesale gasoline price of \$1.67 gallon^{-1}. Furthermore, there has been a steady decline in wholesale price of gasoline paid by producers throughout the year of 2020. March reporting stated that wholesale ethanol prices of gasoline showed it had dropped to \$1.11 gallon^{-1}. The march wholesale ethanol price would be represented by \$1.80 plus \$1.11 (\$2.91) (EIA, 2020).

Switchgrass Yields

Switchgrass yields based on literature from other states are unrealistic for purposes of this research in Oklahoma. However, previously mentioned costs are not useless, yield of biomass per acre/hectare will change the ton^{-1} cost. It is unlikely total removal costs per acre will be changed due to a decrease in yield. Compared to a common case study state (Texas or Indiana), switchgrass in Oklahoma, and for the purposes of this research will be mostly grown on marginal lands in addition to retired wheat acres. Table 4 represents the States of Nature for switchgrass yield which this research will be based on. The yield states are assumptions based on switchgrass production on marginal lands. The overarching goal is to determine a lowest bound and highest bound for switchgrass yield in tons acre^{-1}.

Table 4. Switchgrass Yield States of Nature

State of Nature	Symbol	Yield (tons per acre)	Probability
Bad	S1	1.11	0.157
Average	S2	1.5	0.686
Good	S3	1.89	0.157

Marginal lands have less nutrients, density, etc. than other production field soils. Considering the condition of marginal lands, switchgrass will not have yields similar to other states such as Texas. The lesser yields will be due to switchgrass being planted in shallow soil which does not allow for the plant to become stronger and more established root system to retain more water and grow larger. On marginal lands, the yields will be 1 to 4 tons acre^{-1} year^{-1}, compared to typical production land that could bring up to 8 tons/acre year^{-1} (Caddel et al., 2012). The implications of decreased yields on an Oklahoma switchgrass biomass supply chain will be the need to contract more land and perhaps have a wider area of collection to meet the required tons of biomass per year.

Switchgrass land for biomass is established from a contract between the farmer and bio-ethanol producer. The land in question for our purposes is marginal lands or CRP lands. These lands are able to grow and harvest switchgrass. Compared to other cash-crops, switchgrass will be able to grow with minimal upkeep after the first year, in lesser quality soils such as marginal lands the yields will be less and costs per acre will increase (Jacobson, 2015). The contract is based on past yield data of the farm field location and the contract will be established for the bio-ethanol producer to take all switchgrass biomass that is procured (Lee, 2018). The yields of switchgrass in this case may be higher compared to Oklahoma, using hay as an example, the best-case scenario accounts for 1.89 tons acre^{-1} (Nass, 2017). So, it is important to realize what actual switchgrass yields are when put into practice on lesser quality soils.

Operating Cost

Operating costs are based on a plant with a capacity to process at least 2,000 dry Mg of switchgrass biomass a day (Lee, 2018, Zhang et al. 2012). The required Mg amount translates to 2,200 tons of switchgrass biomass per day. The annual capacity of this biorefinery is about 68.9 million gallons or about 261 million liters per year. Operating at capacity will yield 189 million liters or 50 million gallons of cellulosic ethanol year^{-1} (Lee, 2018). The biorefinery is assumed to operate 24 hours a day, 310 days a year on average, and the minimum feedstock requirement for 2,200 tons of biomass a day is at least 730,000 Mg per year or 805,000 tons year^{-1}. In total, operating costs equates to \$.625 gallon of ethanol^{-1} (Lee, 2018).

Transportation Cost

Transportation for biomass is assumed to account for a large portion of total operational/logistical cost associated with a switchgrass-only bio-ethanol supply chain. For bio-ethanol supply chains with multiple feedstock inputs, the associated transportation costs are lower because of availability of biomass inputs within close proximity to the biorefinery location (Tyner, 2011, Lee, 2018). Trucks involved in moving biomass are assumed to be a flatbed trailer that is 16 meters long and 2.4 meters wide (Tyner, 2011). The trucks are assumed to be able to haul 26 large square bales of biomass from each location. A large bale is estimated to be 863 pounds each (Jacobson, 2014).

Furthermore, Transportation costs associated with biomass hauling to and from the biorefinery will vary based on a number of factors. Total transportation costs per year is a summation of distance fixed, variable, repair, and road damage costs. Distance fixed value is a per mile costs of \$3.10 $mile^{-1}$. Distance fixed value is based on previous literature and adjusted for inflation (Brechbill and Tyner, 2008). Per- ton mile cost is set at a range of values between \$.20 $mile^{-1}$ and \$.40 $mile^{-1}$ (Brechbill and Tyner, 2008, Lee, 2018). Road damage $mile^{-1}$ is set at \$.56 $mile^{-1}$ which is based on a 2011 average value of road class damage by trucks per mile and adjusted for 2020. Lastly, repair costs for trucks per mile is \$.11 $mile^{-1}$ based on previous literature estimates (Barnes and Langworthy, 2003). Repair value is adjusted for 2020 to a value of \$.14 $mile^{-1}$.

Considering each state of nature, there are different distance requirements to collect biomass. To account for increase in mileage, S2 (1.5 tons $acre^{-1}$) will be treated as average tonnage per acre with a required distance of 75 miles to deliver switchgrass. The economic assumption is that with a decrease in tonnage $acre^{-1}$ required mileage to collect biomass is larger. An 11 percent increase in mileage of 84 miles will be used for S1 (1.11 tons $acre^{-1}$). In contrast, S3 (1.89 tons $acre^{-1}$) is treated with an 11 percent decrease in miles required to 67 miles. The values presented for different states of nature are based upon radial distance calculations from Larasati (2012).

Table 5. Expected Cost of Supply Chain with \$.22-ton $mile^{-1}$

Cost Item	Expected Cost (Million/\$)
Building Biorefinery	29.21
Building Storage	21.87
Harvesting Biomass	15.42
Farmer Payment	22.78
Storing Biomass	8.49
Producing Ethanol	30.23
Transporting Biomass	32.50
Total	160.50

Source: Lee, 2018, Griffith et al. 2010

Investment Cost

Costs in Table 5 represent initial investment to establish the feasibility of cellulosic bioethanol production in Oklahoma. Consistent with other states such as Texas, the investment cost of constructing a biorefinery plant is considerably high (Lee, 2018). To establish a starting estimate on fixed (capital) costs, a study on Switchgrass feedstock supply chain was analyzed. The capital costs considerations are derived from a 69-million- US gallon capacity plant. The results of the study concluded that the total capital costs are about $220.1 million (Lee, 2018). Total capital costs represent the investment cost in year “0” or before the supply chain is implemented and production begins.

Capital cost to build a biorefinery is further broken down into sections and is shown in Table 6. Each section is given in millions of dollars- pretreatment ($22.7), conditioning ($9.4), fermentation ($11.2), distillation and solid recovery ($26.1), wastewater treatment ($3.7), storage ($2.4), boiler ($4.6), and utilities ($5.5). The total of the previously listed sections amounts to the total installation costs (Lee, 2018). The remaining difference between the installation and capital cost totals ($93.1) is allocated to miscellaneous costs of installation and construction. The miscellaneous costs can be allocated to labor, transportation, and general maintenance. A buffer is needed in the budget to alleviate issues that arise in construction. The table below (Table 6) shows the breakdown of the total capital costs into the certain allocated categories for a biorefinery. After total capital costs are established, amortization on the total is done over 20 years, using a 7% market interest rate. Based on capital cost data, the estimated per year payment is roughly $20.75 million year^{-1}. Market interest rate of 7% is based on an amortization calculation from a recent thesis dissertation (Lee, 2018).

Table 6. Capital Costs of a Lignocellulosic Biorefinery

Cost Item	Million Dollars ($)
Pretreatment	22.70
Conditioning	9.40
Fermentation	11.20
Distillation and Solid Recovery	26.10
Wastewater Treatment	3.70
Storage	2.40
Boiler	46.00
Utilities	5.50
Total Installation Cost	127.00
Miscellaneous Costs	93.10
Total Costs	220.10

Source: Lee, 2018

Based on a number of factors such as, establishing, maintenance, harvesting, and collecting costs of biomass, the recommended break-even farm gate price is $55 dollars ton^{-1} of switchgrass biomass harvested and collected (Jacobson, 2015). Capital costs of the biorefineryare amortized over a 20-year period. The 20-year time horizon was chosen based on how long it could take to fully establish an ethanol market in Oklahoma. Furthermore, the time horizon is used among much of the previous literature because equipment to convert biomass will be outdated and replaced at a time close to 20 years.

A breakdown budget for the establishment of switchgrass on marginal lands is presented in Table 7. All costs in Table 7 are included in the Net Present Value calculation. However, since the assumption for this research is a contract established between a farmer and ethanol producer, the land rental assumption is subtracted from $189 acre^{-1} to reach a per acre establishment cost of

$144 acre^{-1}. Furthermore, land rent paid to a farmer, labelled as farmer payment, is based upon the 2018 CRP payment of $26.70 to landowners with a 10% premium added to provide incentive for the farmer to produce lignocellulosic biomass. Farmer payment value used in the model equates to $29.37 acre^{-1} (Fewell et al. 2011).

Table 7. Switchgrass Establishment Budget

Cost Item	Unit of Measure	Price Per Unit	Quantity	Value
Land Rental	acre	$45.00	1	45
Switchgrass Seed	Lbs.	$6.00	5	30
DAP (18-46-0)	Lbs.	$0.27	43	11.74
Fertilizer Application	acre	$4.14	1	4.14
Chisel Plow	acre	$11.00	1	11
Disking	acre	$10.00	3	30
Firming Seedbed	acre	$9.00	1	9
Seeding	acre	$13.40	1	13.4
Rotary Mower	acre	$3.50	1	3.5
Herbicide	Oz.	$0.23	18	4.14
Herbicide	acre	$4.50	1	4.5
Herbicide Application	acre	$4.94	2	9.88
Annual Operating Capital	$	$0.07	176.3	12.34
Total Costs	acre			$189.00

Source: (Griffith et al. 2010)

Table 8 represents cost of harvesting switchgrass based on contracting the farm field locations before harvest, harvesting the biomass during a short time frame each year, and eventually contracting the collect all of the available biomass on the land. The contracting scheme will follow an agreement between bio-ethanol producer and farmer to pay a fixed per acre cost for operations to plant, maintain and harvest switchgrass (Hess et al. 2009). The collection operations and associated costs are considered separately from establishing, maintaining, and removal costs. In Table 8, equipment cost is the cost of operating the equipment for harvesting. Within operating cost exists the fixed depreciation costs, fuel, lube, and (if needed) repairs on harvesting equipment. Bulk density refers to the amount of biomass equipment can harvest or the tonnage of biomass that will be contained in each bale. The data is based on the assumption of 15-20 bales at a time to be loaded onto trucks (Hess et al. 2009). Finally, the total operational costs are given in cost dry Mg_{-1} and amounts to $16.44 with an additional variable cost of $1.59. Total value considered in the model equates to $19.88 $acre_{-1}$ ($16.44 + $1.59). Inflated to 2020 dollars, the value is $23.00 $acre_{-1}$ (USinflationcalculator.com). Since there are 1.1 tons to every 1 megagram, the model will continue to use 19.88 because $$23.00_{-1}$ acre is based on a mecagram (Mg) calculation which is greater than one ton.

Table 8. Switchgrass Feedstock Collection Costs

Equipment	Bulk Density	Cost ($)
Self-propelled windrower with disc header	1.14 Mg/300 windrow-meter	3.31± 0.78
275 HP tractor with large square baler	0.58Mg/bale	10.77±1.06
Self-propelled stacker		1.87±0.308
Dry Matter Loss		0.48±0.231
Total Cost ($/DM Mg)		16.44±1.59

Source: (Hess et al. 2009)

Table 9 below is a breakdown of costs used in net present value analysis of operations. The costs presented in Table 9 have been discussed extensively in the previous sections. However, Table 9 presents the data on how each cost item is treated in the model. Furthermore, a visual representation of the actual model input is presenting in Table 10. Example of the model is presented by the average yield state (1.5 tons $acre_{-1}$). Source material for model are presented in

Table 9 and Table 10, each value is presented in 2020 dollars. In Table 10, yellow cells are decision variables where a producer can input their own assumptions for a biorefinery. Orange cells are considered to be reference cells and are locked to users of the tool. While not explicitly shown, green cells represent output of calculations given in a 3x5 table of ton-mile costs and wholesale ethanol prices.

Table 9. Model Cost Item Summary

Source	Cost Item	Unit	Value
Lee, 2018	Per year Payment	Per Year	$20.75 Million
Griffith et al, 2010	Establishing (Seed, DAP, Fert)	Acre^{-1}	$144.00
Fewell et al, 2011	Farmer Payment	Acre^{-1}	$29.37
Hess et al, 2009	Harvesting	Acre^{-1}	$19.88
Lee, 2018	Prod. Costs (Bailing)	Acre^{-1}	$38.95
Lee, 2018	Operating Costs	Gallon Ethanol^{-1}	$0.63

Table 10. Switchgrass Production Cost Sources

Source	Item	Value				
Lee, 2018	Biorefinery Capacity (Gal)	69,000,000.00				Decision Variables
Haque et al. 2014	Financing Rate	7%				Output
Griffith et al. 2010	Project Life (years)	20				Reference Cells
Lee, 2018	Capital Investment ($)	220,100,000.00				
Leboreiro and Hilaly, 2010, A Kumar et al. 2005	Ton-Mile Cost ($)	0.2	0.25	0.3	0.35	0.4
EIA, 2020 (Feb 2020 wholesale price without CWC)	Wholesale Ethanol Price	1.67	1.67	1.67	1.67	1.67
EIA, 2020 (March 2020 wholesale price with CWC)	Wholesale Ethanol Price (w/CWC)	2.91	2.5	2.5	2.5	2.5
EIA, 2020 (Feb 2020 wholesale price with CWC)	Wholesale Ethanol Price (w/CWC)	3.47	3.47	3.47	3.47	3.47
Based on States of Nature (1.11, 1.5, 1.89)	Yield/Acre (Biomass)	1.5				
Larasati et al. 2012 (120km radius)	Miles Per Trip	75				
Lee, 2018	Discount Rate	10%				
Lim and Ouyang, 2016	Conversion Rate (gal/ton)	60				
Brechbill and Tyner (2008) ($2.22)	Distance Fixed Cost	3.1				
Assumption (2/3 of trip)	Backlogging	50.0				
Backlogging + Miles per trip	Average Distance	125.0				

CHAPTER VI

RESULTS

Cost implications of a 69 million gallons capacity biorefinery that yields roughly 50 million gallons of lignocellulosic ethanol year^{-1} are high within the state of Oklahoma. For ease of understanding, results in connection with S2 (1.5 tons acre^{-1}) will be treated as average yield value since the state of nature occurs more frequently than other states of nature. For this research, results of the average yield (S2) will be the main focus of this section. It is assumed that if operations cannot break-even in average years, then in periods of low yields (S1), operations would not realize a net present value in any circumstance presented for this research. In contrast, if average yield state does not realize a positive net present value, there is a chance of increasing yields (S3) would allow for greater revenues per year. However, the main focus of this research is to focus on implications of transportation costs which is greatly affected by yield. In addition, analysis is focused on average yield state situation that is most likely to occur (S2).

A breakdown of costs and revenues per year are given in Figure 4. While net present value of operations is the summation of the present value of profit over the project life, Figure 4 represents what a biorefinery would face per year under specific conditions. Conditions for the case presented in Figure 4 is going to be referred to as the "Average State." Average State is the base of analysis for this research. It is represented by S2 yield state (1.5 tons acre^{-1}), 75 miles to deliver switchgrass biomass (one-way), and \$2.91 gallon ethanol^{-1} which is based upon the realized price of wholesale ethanol for March, 2020. It becomes immediately apparent that in average state total costs exceed total revenues each year. Furthermore, total transportation cost and operating costs of the biorefinery are the two highest cost categories. Transportation costs within Oklahoma are higher compared to other states that may lie in the corn belt (Brechbill and Tyner, 2008, Tyner, 2012). Transportation costs for Oklahoma are considerably high due to lower biomass densification in a county and further required driving distances. In addition, for a 50 million gallon producing ethanol plant, there will need to be 81,707 truckloads per year to deliver the 916,667 tons of required biomass per year. Total truckload value is based on each truck carrying 26 round bales each weighing 863 pounds (Lee, 2018).

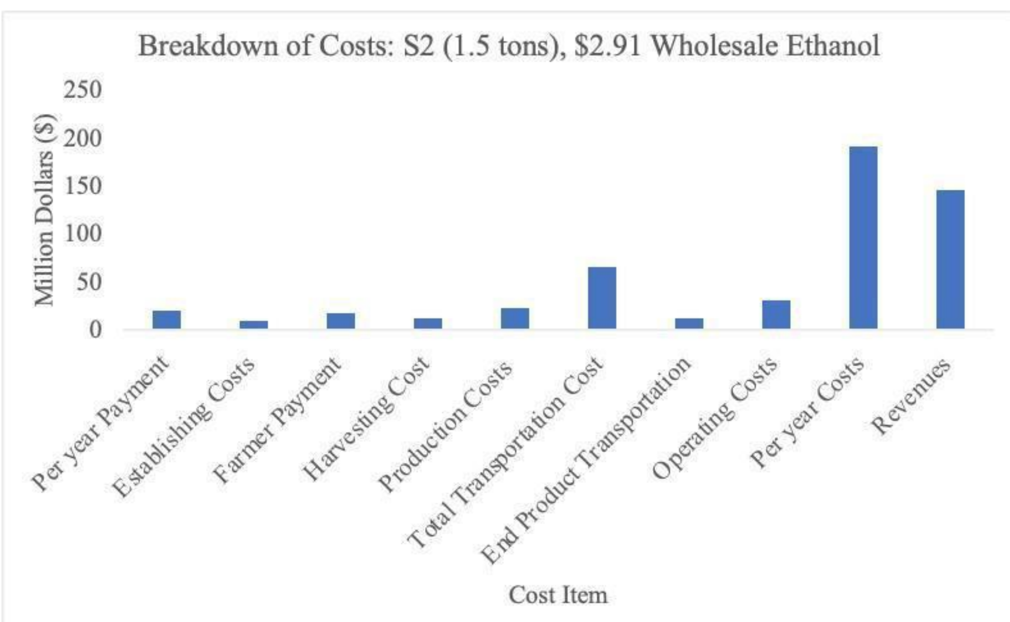

Figure 4. Cost to Produce Lignocellulosic Ethanol in a Given Year at \$2.91 gallon^{-1}

Furthermore, a biofuel project needs to be established over a project's lifetime and determine whether the project is feasible and thus advisable to undertake in certain conditions. For this research purposes, feasibility is based upon average state of nature, S2 (1.5 tons) and is presented over a range of wholesale ethanol prices and variable ton mile costs. Net present value in Figure 5 is over a 20-year project life with a 10 percent discount rate. Wholesale ethanol prices presented in Figure 5 are \$1.67, \$2.91, and \$3.47. \$1.67 gallon ethanol^{-1} represents wholesale ethanol price for February 2020 without cellulosic waiver credit and is presented to represent the importance of subsidizing cellulosic ethanol. In contrast, \$3.47 gallon ethanol^{-1} represents the same February 2020 price in addition to the cellulosic waiver credit for 2020. Results presented in Figure 5 are given in millions of dollars for total net present value at a specific ton-mile cost. It is apparent that in any given situation of ton mile costs presented, at no wholesale ethanol price would an ethanol producer realize a positive net present value. A change in yield acre^{-1} will have to increase tremendously and miles required to deliver switchgrass will need reduction in order for an Oklahoma ethanol plant to be feasible and advisable for an ethanol producer.

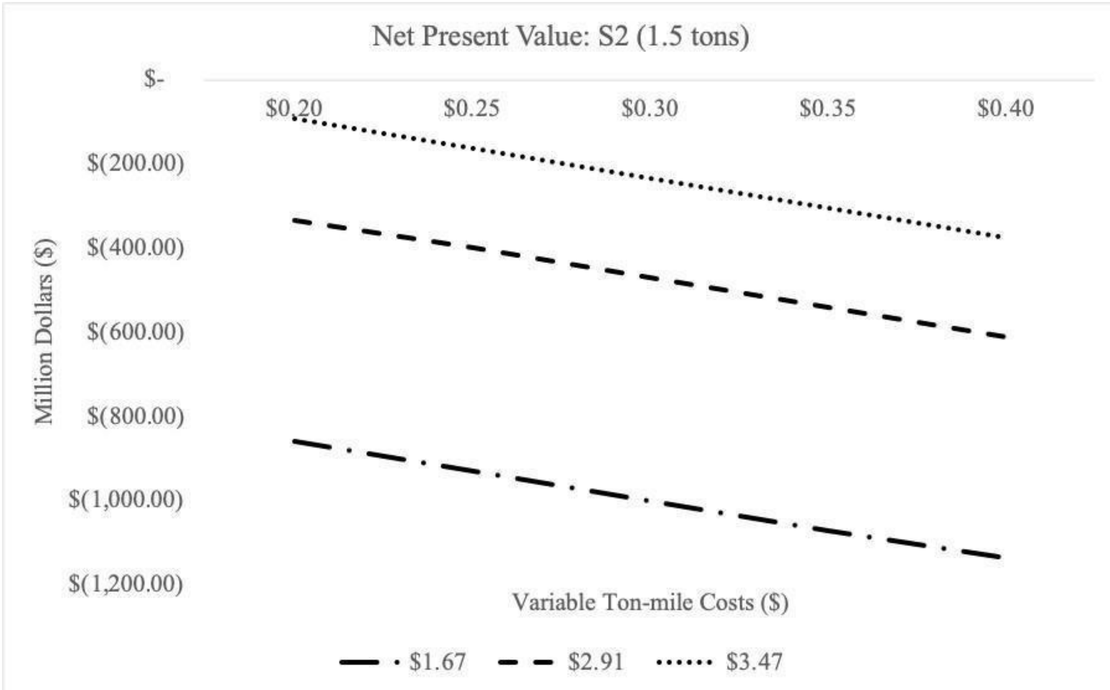

Figure 5. Net Present Value 1.5 Tons Acre-1

In addition to net present value over varying ton-mile costs and wholesale ethanol prices, it is important to establish if an ethanol producer within Oklahoma could break-even given wholesale ethanol prices that are currently realized in the market. To determine feasibility of a project over yield states of nature (S1, S2, S3), a uniform analysis was used. The results presented in Table 11 are a representation of what is currently faced by ethanol producers. A $2.91 wholesale ethanol price gallon-1 with a constant $.20 ton-mile cost assuming a 69-million-gallon capacity (50 million produced gallons) are the base assumptions for the analysis. It can be seen over different states of nature in the current climate it would not be feasible or advisable to begin production of a switchgrass based ethanol supply chain within Calvin, Oklahoma. As shown in

Table 11, no states of nature will have a positive value for operations with the average ($2.91 gallon ethanol^{-1}) wholesale ethanol price.

Table 11. Net Present Value over Yield States of Nature

Plant Location	State of Nature (tons acre^{-1})	Revenue (Million Dollars ($))	Expected Cost (Million Dollars ($))	Expected Profit (Million Dollars ($))
	S1 (1.11)	145.5	213.62	-68.13
Calvin	S2 (1.5)	145.5	184.53	-39.03
	S3 (1.89)	145.5	165.26	-19.76

Last option to determine if an ethanol supply chain is feasible under any circumstance was to investigate whether in the highest yield state of nature available for Oklahoma a producer could realize a positive net present value. Implications for a higher ton acre^{-1} or S3 (1.89 tons) is a lower transportation costs in total. A lower transportation costs is implied due to trucks havingthe ability of gathering more biomass in less fields. Transportation cost implications are high and net present value is sensitive to the varying ton-mile costs as well as mile^{-1} costs because of the less required distance with higher yields. Results of S3 analysis are shown in Figure 6 and further solidified in Table 12 where "0" is not advisable to undertake and "1" is an advisable scenario to undertake cellulosic ethanol production. As can be seen in Figure 6, operations are still mostly negative besides in times where wholesale ethanol price is $3.47 gallon^{-1} and ton-mile cost are below $.25 ton-mile. This can be seen also in Table 12 where only situations where February 2020 wholesale ethanol price with cellulosic waiver credit ($3.47) and ton mile cost of $0.25 or $0.20 were advisable.

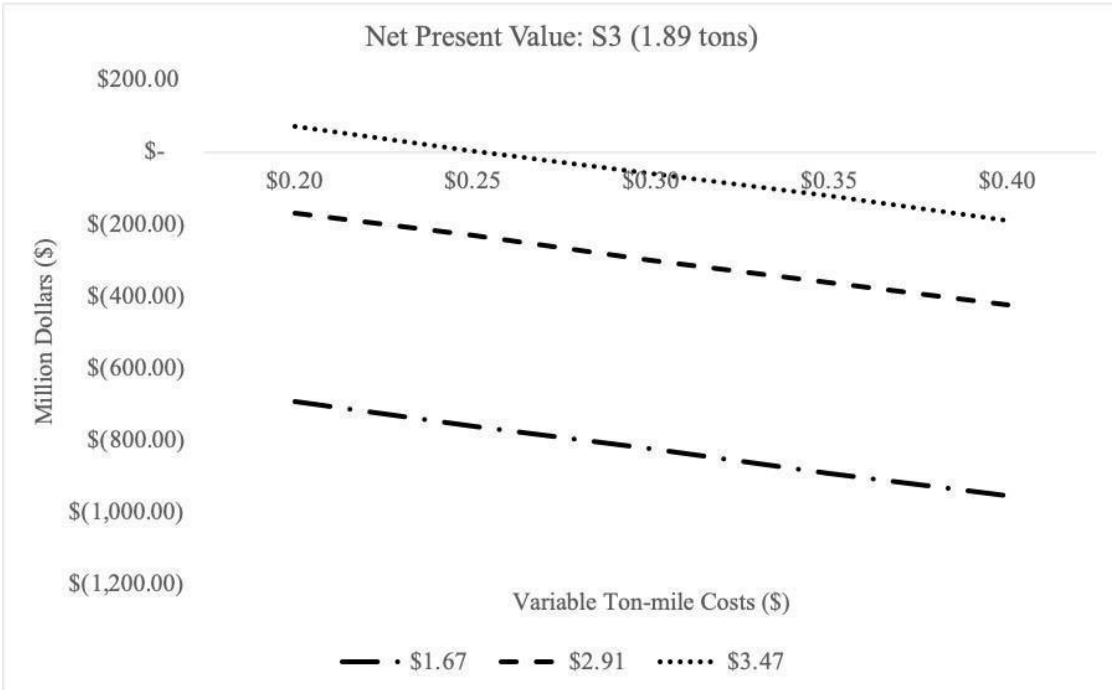

Figure 6. Net Present Value under S3

Table 12. Advisability for S3 ($)

Transportation cost (ton-mile)	1.67	2.91	3.47
0.2	0	0	1
0.25	0	0	1
0.3	0	0	0
0.35	0	0	0
0.4	0	0	0

CHAPTER VII

CONCLUSION

Since the passing of the Energy Independence and Security Act, there has been a need to establish a commercial renewable ethanol sector within the United States. For a developed and commercially successful cellulosic biofuel plant within Oklahoma, ethanol producers must maximize and realize a positive net present value over the life of a project. Producers of cellulosic ethanol and more specifically, Oklahoma based cellulosic ethanol producers must realize various impacts of transportation costs on rural infrastructure. Realizing impacts allows for quantifiable damages and the impact on the biorefinery's returns above costs.

Cellulosic based ethanol has advantages in utilizing non-food feedstocks as inputs. In addition, government subsidies assist a cellulosic ethanol producer in being competitive with petroleum-based fossil fuels. Transportation costs present the greatest hurdle to an Oklahoma based cellulosic ethanol producer. Furthermore, the choice of location is based on the least cost route to deliver biomass. Through further research, transportation costs can be more refined to improve profitability. A comparison of Oklahoma to a state with higher rural infrastructure is important to realize implications of higher transportation cost. Oklahoma has advantages as well as many drawbacks to ethanol production when compared to other states with a busting corn market (Brechbil and Tyner, 2008, Tyner, 2012). Oklahoma has advantages in utilizing marginal, CRP, or retired wheat acres to produce cellulosic biomass but is limited in terms of infrastructure and rural road access. An Oklahoma cellulosic ethanol supply chain would realize 81,707 truckloads year^{-1} to deliver switchgrass. Compared to 55,182 truckloads year^{-1} required for an ethanol producer in Indiana (Tyner, 2012). Both truckloads are based on a 50 million gallon yielding biorefinery. By default, there will be less damage to road infrastructure with fewer truck loads required year^{-1}.

To improve upon required truckloads, Oklahoma will have to realize assumptions faced by other states. For example, previous studies in Indiana were presented with an ideal situation of 1.6 to 3 tons of removable biomass acre^{-1}, higher removal rate of 37 percent acre^{-1}, corn stover as an additional input, and the use of concentric circles to derive optimal distance from biorefinery (Brechbil and Tyner, 2008). Oklahoma producers are faced with 1.11 to 1.89 tons of removable feedstock, a lower removal rate, and a switchgrass only based input. Higher number of tons of biomass available because of a higher removal rate and multiple feedstock options allow for less truckloads required, thus allowing for less transportation cost as a whole. Lastly, it is important to note that the inclusion of road damage cost is unique to an Oklahoma analysis and accounts for nearly $5.7 million added to transportation costs each year, based on 75 miles per trip and 81,700 truckloads year^{-1}. Corn-belt states typically do not have to include this due to quality of infrastructure and availability of roads (Tyner, 2012).

This study finds without higher availability of single sourced biomass, and less damage to inferior road infrastructure each year, Oklahoma ethanol producers will not realize a positive net present value under average yield state conditions. An Oklahoma ethanol producer can only realize a positive net present value under S3 conditions. Breakeven conditions are established where yield acre^{-1} is 1.89 tons, 67 miles trip^{-1}, wholesale ethanol price gallon^{-1} of $3.47, and a variable ton mile cost of $0.25 or under. Transportation cost represents the main source of cost for Oklahoma. Without an improvement in infrastructure or yields, Calvin, Oklahoma, on average, is not feasible or advisable for the production of switchgrass-based cellulosic bioethanol.

Overall, it is apparent that without government intervention in the form of subsidies, improved infrastructure, and increased yields of biomass that Oklahoma ethanol production is not feasible in the current market. However, it is interesting to note that if this project were to be undertaken in February 2020 and higher-than-average yields existed there are instances where the project is profitable. The main conclusion of this research is without government intervention an ethanol producer could never compete with gasoline or turn a profit due to high transportation costs. Further research could be done to answer how Oklahoma could improve rural economy and thus improving the infrastructure and how to improve yields on marginal lands. Last side note is to bring light to a post-coronavirus pandemic world where the demand for petroleum-based gasoline is lower.

Further research could provide implications to a cellulosic biofuel industry when gasoline has little to no inherent value. Gasoline has no value when demand for the product is low similar to the current Coronavirus climate the world is faced with today. For future research, it would be interesting to see the implications higher yields would have on total transportation cost as a whole. This could provide an incentive to Oklahoma to improve yields if profits are realized with increasing yields. Furthermore, it would be interesting to see how an Oklahoma based producer could produce second generation ethanol with multiple feedstock options.

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